

Report for 2005IN173B: The Effects of Landscape Transformation in a Changing Climate on Indiana's Water Resources

Publications

- Conference Proceedings:
 - Goss, A.M., C. E. Davis, D. Tripathy. The Effects of Landscape Transformation in a Changing Climate on Indiana's Water Resources. Indiana Water Resources Association Symposium, West Lafayette, IN, June 2006.
- Dissertations:
 - Davis, C.E. Understanding and Managing the Impacts of Climate Change in a Complex Environmental System: The Effects of Increasing Precipitation and Land Use Change on Streamflow. Dissertation. Advisor: Jon Harbor. Expected graduation: May 2007.
 - Goss, A.M. Assessing the Historical Impacts of Landscape Transformation on Water Fluxes in Muskegon River Watershed for Environmental Monitoring and Assessment. Dissertation. Advisor: Jon Harbor Expected graduation: May 2007.

Report Follows

THE EFFECTS OF LANDSCAPE TRANSFORMATION IN A CHANGING CLIMATE ON INDIANA'S WATER RESOURCES

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PROBLEM AND RESEARCH OBJECTIVES

Indiana's landscape has been rapidly changing in the last fifty years - a change that often has unintended consequences on the state's water resources. The nine-county Greater Indianapolis area (Boone, Hamilton, Hancock, Hendricks, Johnson, Madison, Marion, Morgan, and Shelby counties) has undergone a dramatic population increase in the past several decades, which has increased the demand for local water resources (Figure 1). The growth rate (16.4%) of Greater Indianapolis exceeded the national average (13.2%) for the period 1970 to 2000, with Hamilton County showing a 404% increase (U.S. Census Bureau, 2000). Combined with this increase in demand, it is well understood in general terms that the urban development accompanying population increases also shifts the balance between surface and groundwater, with direct impacts on both water supply and flooding. Nationally, interactions between land use change and hydrologic processes are recognized as a major scientific and management challenge (National Science Foundation, 2003; DeFries and Eshleman, 2004) and in Greater Indianapolis, as well as other Indiana cities, managing growth based on an understanding of past and future impacts of land use change on water quality and quantity is critical if we are to sustain the economic and environmental health of the state.

Urbanization affects local hydrology by increasing impervious surface area, which reduces infiltration and results in more direct surface runoff. Urbanization also affects flood timing and magnitude, streamflow regime, stream channel and soil erosion, aquatic habitats, and groundwater recharge. Nationally, flooding causes approximately \$3.1 billion in damages (Pielke Jr. and Downton, 2000) and can spread disease through direct pollutant runoff and overloading of treatment facilities (Ford *et al.*, 1998). Effective management of excess rainfall and runoff is an important issue to consider for Indiana's economy and environmental health. Surface water quality is impaired not only by the elevated amount of pollutants present in an urbanized area, but also through the channelization of runoff directly into the streams by the paved surfaces. Water carries pollutants into the soil as it infiltrates, which allows for natural degradation of contaminants by microbial processes. When pollutant-laden runoff is prevented from infiltrating, the contaminants are directly transported to streams, where the degradation process is much slower, if present at all.

Another impact of urbanization is its ability to significantly alter baseflow — the sustained flow in a stream that comes from groundwater discharge or seepage. This discharge often maintains streamflow during seasonal dry periods and has important ecological and environmental functions. Precipitation that infiltrates into the subsurface becomes groundwater, providing baseflow to streams. Decreased infiltration rates and increased groundwater withdrawals from aquifers underlying urban areas have the potential to reduce baseflow in

streams and water level in lakes and wetlands. Lowered baseflow can impose limitations on long-term availability of groundwater and can adversely affect stream resilience to drought conditions.

Greater Indianapolis' water supply comes from a combination of public reservoirs and public and private groundwater wells and is threatened by increasing urbanization. Not only has the water demand increased (Arvin and Spaeth, 2000), but the amount of water reaching regional aquifers may be decreasing due to increased impervious surfaces. Reservoirs used for drinking water supply may also be affected by increased stresses, such as extreme floods and droughts, reduced groundwater recharge, and elevated pollutant loads. In order to support planning for growth in Greater Indianapolis, the past and future impacts of urbanization on natural hydrologic functions must be ascertained.

This study furthers our understanding of watershed processes and the relationship between urbanization, precipitation, streamflow, and groundwater. Through the integration of urban land use scenarios with historical water fluxes and climatic data, the project will provide an assessment of impacts to stream discharge, baseflow, and hydrograph peaks (flooding).

The lack of studies focusing on the integrated details of watershed hydrology, urbanization, and climate change makes this project important because it focuses on improving our understanding of process interactions in a complex environmental system responding to climate change. Integrating models that address urbanization, hydrology fluctuations, as well as climate change scenarios enable the assessment of future consequences of land use change and climate scenarios on water resources, and consequently, to address policy questions related to the sustainability of current resources. This provides a basis for predicting future streamflow, baseflow, and hydrologic variations resulting from climate change, urbanization, and the combination of the two.

The U.S. EPA Office of Research, through its "Water and Watersheds" program, has identified the need for greater emphasis on watershed management based on improved understanding of how human activities impact water resources (EPA, 1998). The research conducted in this project includes an investigation of how human modifications of landscape, combined with observed and modeled climate scenarios, affect water cycling at various scales in the Greater Indianapolis area. We investigate this issue through combining recreations of historical land use ("backcasts") with hydrologic models that predict surface and subsurface water flows in the Greater Indianapolis area. Through analysis of human impacts on water resources in this region, for which land use change is a proxy, the influence of climate change on the hydrology of this region can be indirectly assessed.

Our primary objectives are:

- (1) To determine the historical relationships among urbanization, climate, and hydrology (specifically, streamflow, peak flows, and baseflow) in the Greater Indianapolis area
- (2) To evaluate the implications of past relationships for informing decisions about future change
- (3) To create an approach that can be applied across the entire state of Indiana for more comprehensive water resource management.

METHODOLOGY

To quantify the interactions between historical hydrology and land use in Greater Indianapolis, we employed both actual and projected precipitation, streamflow, and baseflow values for three urbanizing watersheds. The watersheds were selected based on the availability

of continuous streamflow and precipitation data. Modeled data were coupled with estimated urban, agricultural, forest, and shrubland/grassland areas for pre-1940 and present using U.S. Census and National Agricultural Statistics Service (NASS) datasets for selected watersheds in Greater Indianapolis. We used Purdue University's web-based L-THIA watershed delineation tool (Choi *et al.*, 2002) and combined these delineations with the USGS National Hydrography Dataset (NHD) (USGS, 2004). Historical hydrologic data were combined with modeled historical land cover data and water fluxes to determine the relative impacts of urbanization and climate change on streamflow, baseflow, and flooding. Distinguishing the impacts of natural from human-induced impacts on streamflow and baseflow was predicted through analyzing the changes to hydrology while land use and climatology remain static. Historical peak annual and seasonal discharge records were examined for the three Greater Indianapolis watersheds to determine whether these events have changed over time and if there is a trend in the data record. Flood frequencies and magnitudes were also calculated from the historical streamflow record to determine whether the risk of flooding has changed over time.

Quantifying Interactions between Hydrology and Land Use

Streamflow and baseflow variations are a result of the combined impacts of natural and anthropogenic influences. For this study, we focused on climate change and land cover change (primarily urbanization) as the primary factors impacting streamflow and baseflow in Greater Indianapolis over the past 60 years. Three stream gauges and accompanying watersheds were identified for analysis: Fall Creek near Fortville, Fall Creek near Millersville, and Little Eagle Creek at Speedway (Figure 2). Historical and predicted streamflow, baseflow, and precipitation were statistically examined to (1) quantify the relative influences of natural and anthropogenic variation on streamflow and baseflow and (2) to evaluate the amount of variation in streamflow, baseflow, and precipitation in Greater Indianapolis.

Determining the change in streamflow, baseflow, and precipitation data required statistical trend analysis of whether the data is increasing, decreasing, or remaining stationary over a given period of time. Use of the Mann-Kendall Rank Correlation Test allowed for both the detection of monotonic trends and the significance determination of the trends. The Mann-Kendall test is a common method for determining the presence of trends in hydrologic data (Lins and Slack, 1999; Stogner, 2000; Pilon and Yue, 2002) since it is a non-parametric test, resistant to the skewing influences of outliers (Helsel and Hirsch, 1992). The identified trends were used to consider future implications of land transformation and climate change on Greater Indianapolis water resources. Regression techniques were used to determine the relative amount of streamflow and baseflow variation accounted for by climate and urbanization.

Completing the Land Use Record

In order to input historical estimates of land cover into a hydrology model, the operational unit of the historical data used to derive estimates must be converted to the resolution of the hydrology model. Historical land use scenarios spanning 60 years a selected watershed in Greater Indianapolis were developed based on demographic and land use databases at the minor civil division (MCD) and county level. The VIC (Variable Infiltration Capacity) model calculates water fluxes within grid cells using percent cover of each land use type defined within the model.

The VIC model is an energy and water balance system (Liang *et al.*, 1994; Liang *et al.*, 1996; Cherkauer *et al.*, 2003). In comparison to other Soil-Vegetation-Atmosphere Transfer

Schemes (SVATS), VIC is able to model variability in soil moisture capacity as a probability distribution, as well as parameterize baseflow, so that it is separated from quick storm response (Zhao *et al.*, 1980; Dumenil and Todini, 1992). The model relies on a vegetation library file that provides information, such as leaf area index and albedo, for each land use type. These figures were derived and provided to the model for urban areas. Evapotranspiration, surface runoff, and baseflow were then computed for each cover type and summed over all cover types within a grid cell. The outputs include energy and water balance flux information, as well as outflow hydrographs. Four land use types were used to characterize the historical landscape of the study area: urban (impervious), agricultural, shrubland/grassland, and forest.

Large-scale land use data for the study area is limited by the availability of reliable remotely sensed data which emerged in 1978 with the Landsat TM satellite images. Using a technique pioneered by Goss *et al.* (2005), United States Census data was used for estimates of urban growth in the time period before present-day. Total housing units data for each time period were derived from the “Year Built” statistic (referred to as “QT-H7 Year Structure Built and Year Householder Moved Into Unit” or “Occupied Housing Units” within the Summary File 4 dataset for the 2000 Census) (U.S. Census Bureau, 2000). The number of houses built before 2000 (used to represent “present” because it is the last available Landsat TM image) in each township was calculated. Using the number of houses built during each time step, the amount of impervious area that existed during that time step could be estimated for the operational unit of the hydrology model used.

The National Agriculture Statistics Service (NASS) Census of Agriculture served as a proxy for agricultural data. On a county basis, it reports the number of acres that are agricultural (called “Land in Farms”) (U.S. Census Bureau, 1980). Decadal values were normalized by the ratio of Land in Farms in 2000 to agricultural land cover in 2000 (taken from Landsat TM data) for each county. These values were corrected by area-weighting the spatial relationship between each county and each VIC grid cell, which provided the percent agricultural for each VIC grid cell.

The percent of each VIC grid cell that was covered by the remaining two land uses/covers—shrubland/grassland and forest—was created through employing a transition matrix for the watershed from 1978 to 1998. The ratios of change from and to each of the four land uses were combined with the estimated urban and agricultural values for 1940 to generate estimates of shrubland/grassland and forest for VIC grid cells. In this way, the output of the model was land cover for 1940, a time for which reliable historical land use data is not available.

Completing the Streamflow and Baseflow Records

50 years of continuous data are often recommended to determine and analyze trends in hydrologic data (Lettenmaier *et al.*, 1994; Stogner, 2000; McCabe and Wolock, 2002). The entire period of historical streamflow and corresponding precipitation data available for the three study sites was used in this analysis. Fall Creek at Fortville and Fall Creek at Millersville had 63 and 75 years of available data, respectively. Although Little Eagle Creek had only 45 years of streamflow data, this was deemed sufficient. Since all three watersheds were gauged, daily streamflow data was obtained from the U.S. Geological Survey website (USGS, 2006) and daily precipitation data was accessed through the National Climatic Data Center website (NCDC, 2006).

Baseflow can be separated from the historical streamflow data using various hydrograph separation techniques. The Web-based Hydrograph Analysis Tool (WHAT) is a convenient

method for baseflow separation (Engel and Lim, 2004). This automated hydrograph separation method is based on flow peak and flow minimum detection from continuous stream flow data and produces results comparable with another widely-used program - HYSEP (Sloto and Crouse, 1996).

Analysis of frequency and magnitude of extreme hydrologic events

Extreme value distributions from the historic precipitation and streamflow data were used to determine the magnitude of rainfall and discharge events with various recurrence intervals. Due to the increased amount of impervious surfaces, rapidly urbanizing areas are at risk for unexpected flooding events, requiring this flood frequency analysis for the Greater Indianapolis area. This analysis was also used on the precipitation data record to consider the potential effects of climate change on extreme precipitation events. To best determine the change over time, the flood frequency analysis was used in combination with a 10-year moving window. Use of moving window analysis for a set length of time reduces the influence of record length on extreme event statistics.

RESULTS AND DISCUSSION: HISTORICAL PRECIPITATION

Mann-Kendall trend analysis indicated no statistically significant trends in peak annual daily precipitation or total annual precipitation for the three study sites (Tables 1 and 2). Seasonal precipitation analysis, however, did show that autumn precipitation in the Little Eagle Creek watershed is increasing. Peak autumn daily precipitation and total autumn precipitation both show statistically significant increasing trends in the Little Eagle Creek watershed. Linear regression was also conducted on total annual precipitation and resulted in essentially no change (P value is 0.46, 0.61, and 0.44 for Fall Creek near Fortville, Fall Creek near Millersville, and Little Eagle Creek at Speedway respectively).

The timing of peak precipitation events was also examined to determine whether peak precipitation events were correlated with peak discharge events. As expected, most peak precipitation events occur in the summer months of June and July, while peak streamflow events tend to occur in the late-winter (February) and spring (May) due in part to snow melt. At Little Eagle Creek and Fall Creek near Fortville, approximately 30% of peak daily precipitation events were directly correlated to peak daily streamflow events. This correlation is a bit lower (23%) for Fall Creek near Millersville. These findings indicate that over two-thirds of peak daily precipitation events do not directly cause peak streamflow events. Many peak streamflow events were the result of extended rainy periods, rather than a single heavy rainfall event. Further examination of the relationship between seasonal precipitation and streamflow indicates that the peak events are occurring in concert with one another more frequently in the later part of the record (Figure 3).

Precipitation statistics were examined to determine whether high-magnitude, low-frequency precipitation events are changing over the period of record for the three sites. Due to the varying record lengths available, a moving-window analysis was used to obtain precipitation statistics for uniform record lengths. The Extreme Value Type 1 distribution was chosen because of its suitability for modeling storm rainfall (Chow et al., 1988). It was found that for the 24-hour events of all recurrence intervals, there has been no consistent change over the period of record. This suggests that high-magnitude precipitation events are not becoming more frequent or intense.

RESULTS AND DISCUSSION: HISTORICAL BASEFLOW

Baseflow in all the three urbanized watersheds in the greater Indianapolis region has increased significantly over the years as shown in Figure 4 to 6. Similar increasing trends in baseflow are also found using the Mann-Kendall test for all the three watersheds (significance level is 0.009, 0.007, and 0.0005 in the watersheds of Fall Creek near Fortville, Fall Creek near Millersville, and Little Eagle Creek at Speedway respectively). 10-year moving averages of baseflow also show a definite increase in trend (Figures 7 to 9). It is also important to note that, as expected, the direct runoff has increased appreciably in all the watersheds (Linear regression P value is 0.41, 0.05, and 0.001 in the watershed of Fall Creek near Fortville, Fall Creek near Millersville, and Little Eagle Creek at Speedway respectively). Increase in direct runoff results from increased impervious area associated with progressive urbanization.

Even if there is a significant increase in annual baseflow in all the three urbanized watersheds, there is hardly any change in annual precipitation. Thus, in order to further examine the influence of urbanization on the three watersheds, the normalized baseflow (normalized with respect to precipitation) were analyzed for their trends. As shown in Figures 10 to 12, the normalized baseflow in all the three watersheds again showed significant increasing trends. Similar increasing trends in baseflow were also found using the Mann-Kendall test for all the three watersheds (significance level is 0.001, 0.003, and 0.0001 in the watersheds of Fall Creek near Fortville, Fall Creek near Millersville, and Little Eagle Creek at Speedway, respectively). 10-year moving averages of baseflow also show a definite increase in trend (Figures 13 to 15). The results clearly indicate that progressive urbanization had played a major role in the increase in baseflow in all the three watersheds as opposed to influence of climate (as detected through precipitation).

RESULTS AND DISCUSSION: HISTORICAL STREAMFLOW

Mann-Kendall trend analysis for the three watersheds indicates that substantial changes have occurred in peak annual and peak seasonal streamflow, although not all trends are statistically significant (Table 3). Little Eagle Creek has experienced the greatest change in peak streamflow, with statistically significant increasing trends in peak annual, peak summer, and peak autumn streamflow (Figures 16 to 18). Both Fall Creek sites had statistically significant increasing trends in peak autumn streamflow and Fall Creek near Millersville also showed a statistically significant increasing trend in peak summer streamflow.

Further investigation into autumn streamflow indicated that a low percentage (approximately 10%) of peak annual events occur in autumn at all sites, so the changes observed in peak annual streamflow are probably not driven by the autumnal increases. This is important for local water resource managers, as a shift from the typical late-winter/early-spring peak discharge to autumn would result in very different management practices. Heavy streamflow occurring early in the growing season is important for crop productivity, as well as providing the basis for drinking water and recreational reservoirs. Since the peak autumn streamflow trends were so strong at all three sites, further investigation is needed to determine if this matches a regional pattern of streamflow change.

RESULTS AND DISCUSSION: FLOOD MAGNITUDE

Extreme value distributions from the historic data were used to determine the magnitude of high discharge events with various recurrence intervals. Rapidly urbanizing areas are at risk for unexpected flash flooding events, requiring this analysis for Greater Indianapolis. A 10-year

moving window analysis indicated that flood magnitude has not experienced a dramatic change over the period of record. This could largely be the result of dams in the upper reaches of the watersheds, which serve to regulate the discharge of water at both sites.

RESULTS AND DISCUSSION: MODELED LAND COVER CHANGE AND WATER FLUXES

The use of a distributed hydrologic model enables the identification of spatial trends in water fluxes within a watershed that could not be detected by simply examining a point value of baseflow or streamflow at a basin's outlet.

The spatial pattern of modeled monthly baseflow is similar throughout the year. The southern half of the watershed showed little response to the change in land cover input (Figure 19). Most of the northern portion of the watershed demonstrated a slight increase. However, one cell modeled a dramatic difference between the two land uses. The baseflow generated from the 2000 land cover input was 43% lower than the baseflow generated from the 1940 land cover (from ~925 mm to ~650 mm per month). The yearly average baseflow over the 50 year period was ~2,500 mm (100 inches) higher with the 2000 land cover than with the 1940 land cover.

Modeled evaporation showed similar spatial trends from October to June. The southern portion of the watershed had similar values between both land cover inputs with slightly higher evaporation values in the middle of the watershed (Figure 20). The northern portion of the watershed modeled slightly lower evaporation values, except for the east central cell which produced consistently higher evaporation each month on the order of 75% (a maximum difference of ~23 mm).

Excluding this cell, the monthly average evaporation was lower for the 2000 land cover input than for the 1940 land cover in the months of July, August, and September. The largest differences were in the northern half of the cell, reaching over 100% reduction from 1940 values to 2000 values. These values represent a difference in evaporation of ~10 mm (0.4 inches).

Most of the watershed modeled similar runoff values with the two land covers through the winter and early spring (Figure 21). These values deviated through the rest of the year reaching maximum deviation in October and November. Most of the watershed produced lower runoff values for the 2000 land cover than for the 1940 land cover, yet most of the difference between cells was within 50%. The east central cell with higher precipitation inputs, produced some of the largest differences between the two land covers, in some months 70% less runoff (13 mm vs. 8 mm) was produced with the 2000 land cover than the 1940 runoff. The total runoff generated by cells within the watershed was slightly larger with the 1940 land cover than the 2000 land cover (3114 mm and 2833 mm respectively).

The land cover change estimated by the above method bases estimates of urban area on the ratio between housing units and urban cover in 2000. This produced an increase in urban area over the 50 year time period on the order of 80 km² within the watershed (Figure 22). While urban is a small percentage of the total land cover, this change represents a 230% increase in urban area over the 60 year time period. Agricultural and forest coverage both decreased substantially (220 km²/20% and 130 km²/55% respectively). The largest change by area in land cover occurred within shrubland, which increased by 275 km² or 30%. This land cover change scenario helps to explain the lack of an increase in runoff. Generally, agriculture produces more evapotranspiration and runoff than shrubland within the VIC framework. A decrease in forest cover and increase in urban cover should increase runoff, yet the increase in shrubland attenuated this change.

SIGNIFICANCE OF THE PROJECT

This project provides water resource managers with information they need to evaluate and manage critical changes in water resources related to land use and climate change. This work has important implications for both science and society through its consideration of climate change, land use, and watershed management, and helps further our understanding of watershed processes and the relationship between urbanization, precipitation, streamflow, and groundwater. Through the integration of urban land use scenarios with historical water fluxes and climatic data, this project provides an assessment of impacts to stream discharge and baseflow. The work outlined here provides a basis for predicting future streamflow, baseflow, and hydrologic variations resulting from climate change, urbanization, and the combination of the two. The key benefits of this project are:

- (1) Quantification of past and predicted water cycle fluxes in Greater Indianapolis, including an understanding of the causal relationships
 - a. There is no significant trend in precipitation over the period of record.
 - b. Streamflow is increasing, with the most dramatic increases in autumn.
 - c. Baseflow is increasing over the period of record.
 - d. Land cover changes within the Fall Creek near Fortville watershed were estimated. Urban cover has more than doubled since 1940 while agricultural and forest cover has decreased. Shrubland and grassland cover has increased.
 - e. These estimated changes have caused modeled baseflow to increase, runoff to decrease, and evaporation to decrease. The spatial distribution of these water fluxes enriches the historical streamflow and baseflow records at the watershed's outlet.
- (2) Provide water resource managers with integrated information necessary for sustainable growth in Greater Indianapolis
- (3) Creation of a comprehensive framework that is transferable to the rest of Indiana and the U.S.
- (4) Public education regarding the important societal implications of altered water resources in Greater Indianapolis

The information generated in this study can be used in developing approaches to minimize the effects of upstream urban land uses on downstream processes, and will also be used in a reevaluation of current watershed planning. A better understanding of the water and energy fluxes between land, atmosphere, and hydrology enables the development of strategies to mitigate the impacts of future landscape transformation and climate change. Engineering design, such as that for bridges and culverts, normally based on out-dated streamflow and precipitation records may be shown to be noncompliant and obsolete in the context of current data. Knowledge of current streamflow regimes and prediction of future effects on flood frequency and magnitude will allow for better planning and mitigation of damage, and a better understanding of how environmental systems respond to both climate change and urbanization. An improved understanding of how Indiana watersheds function and how human activities (such as urbanization) impact water resources enables environmental agencies, such as the Indiana Department of Natural Resources and the Division of Water, to manage water resources more effectively.

STUDENTS

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DISSERTATION TITLES, PAPERS, AND ABSTRACTS

Davis, C.E. Understanding and Managing the Impacts of Climate Change in a Complex Environmental System: The Effects of Increasing Precipitation and Land Use Change on Streamflow. Dissertation. Advisor: Jon Harbor. Expected graduation: May 2007.

Goss, A.M. Assessing the Historical Impacts of Landscape Transformation on Water Fluxes in Muskegon River Watershed for Environmental Monitoring and Assessment. Dissertation. Advisor: Jon Harbor Expected graduation: May 2007.

Goss, A.M., C. E. Davis, D. Tripathy. The Effects of Landscape Transformation in a Changing Climate on Indiana's Water Resources. Indiana Water Resources Association Symposium, West Lafayette, IN, June 2006.

Abstract: Water resources are critically influenced by changes in land use and climate. As landscapes are converted from agriculture to urban and suburban development, natural hydrologic processes are altered. Impervious surfaces decrease the amount of water infiltrating into the soil to become groundwater and increase the amount of runoff reaching streams. Similarly, climate change that increases the frequency of large rainstorms alters the amount of runoff and groundwater, even if average annual rainfall remains constant. The Greater Indianapolis area has been experiencing increased urbanization in the past several decades, which is affecting the local water quality and quantity. As population increases, the stresses placed on water resources also increase. This project quantifies the impacts that past and future land use and climate change have on Greater Indianapolis water resources, providing critical information for local water resource planners and managers who are working to protect the water resources that are vital for the economic and environmental health of Indiana.

Tripathy, D. Assessing Land Use Change Impacts on Groundwater Resources. Dissertation. Advisor: Jon Harbor. Expected graduation: May 2007.

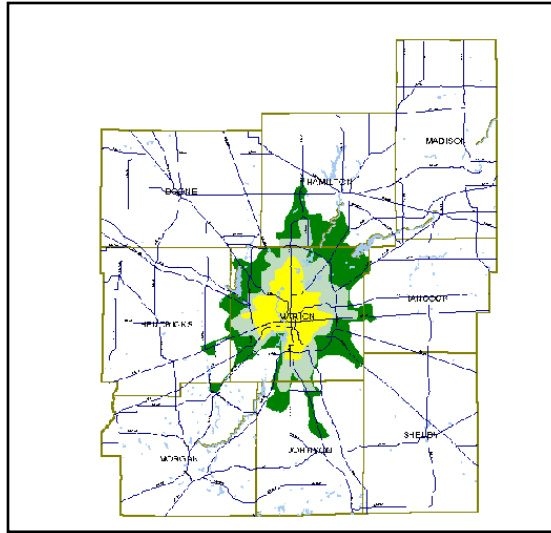


Figure 1. Historical growth of the Indianapolis urban area in the nine-county Greater Indianapolis area. Yellow indicates the contiguous developed area in 1963, grey shows the urban growth through 1895, and the green area is the contiguous developed area in 1999. In 1963, the Indianapolis metro area was completely contained in Marion County. (From Stumpf, 1999)

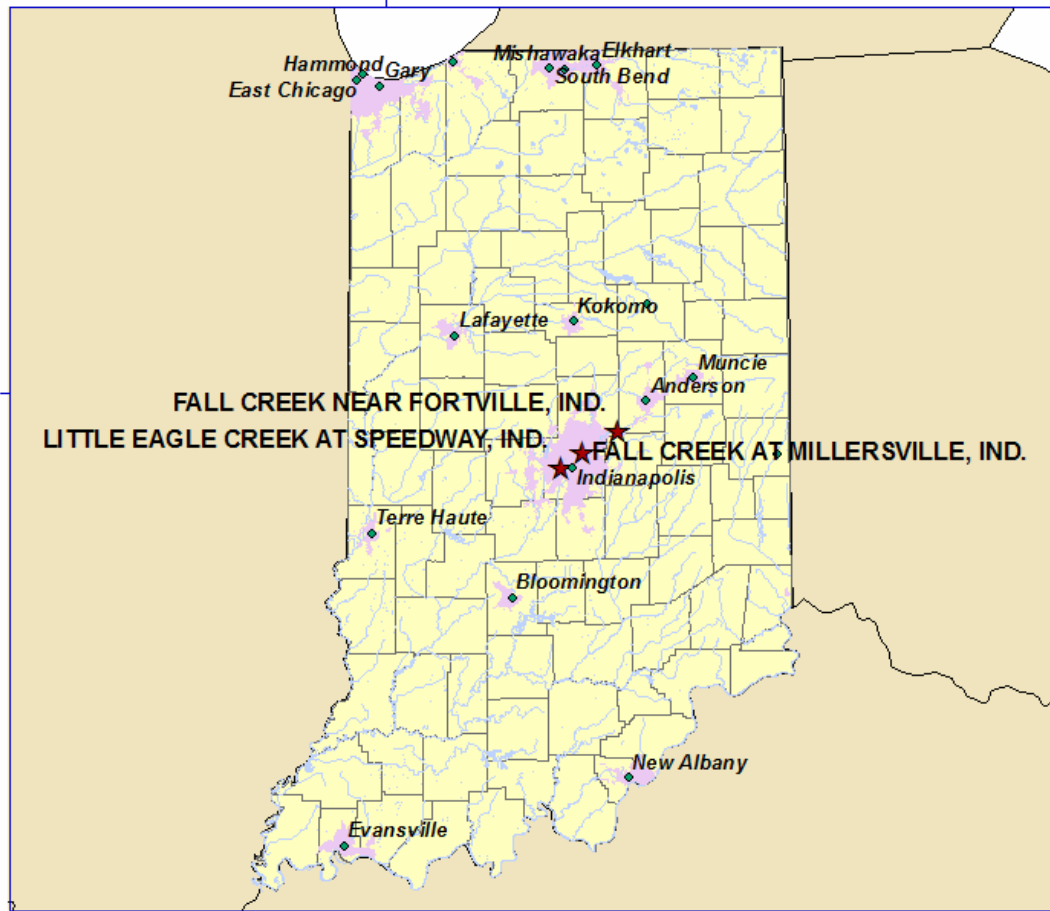


Figure 2. Location of streamflow gauges and watersheds analyzed in this study.

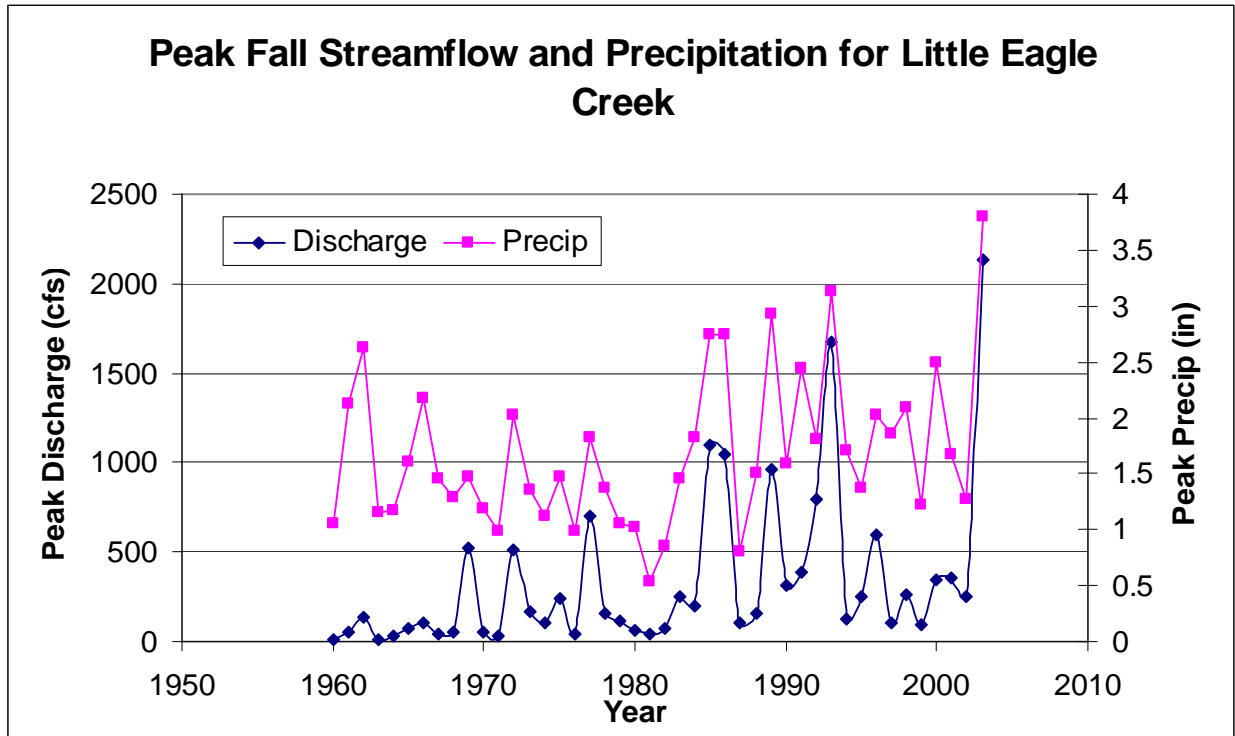


Figure 3. Relationship between peak autumn precipitation and streamflow for Little Eagle Creek. Prior to 1980, precipitation and streamflow appear to be changing in opposite directions, with precipitation decreasing and streamflow increasing. After 1980, however, the peaks are more aligned, indicating a greater relationship between peak autumn precipitation and peak autumn streamflow.

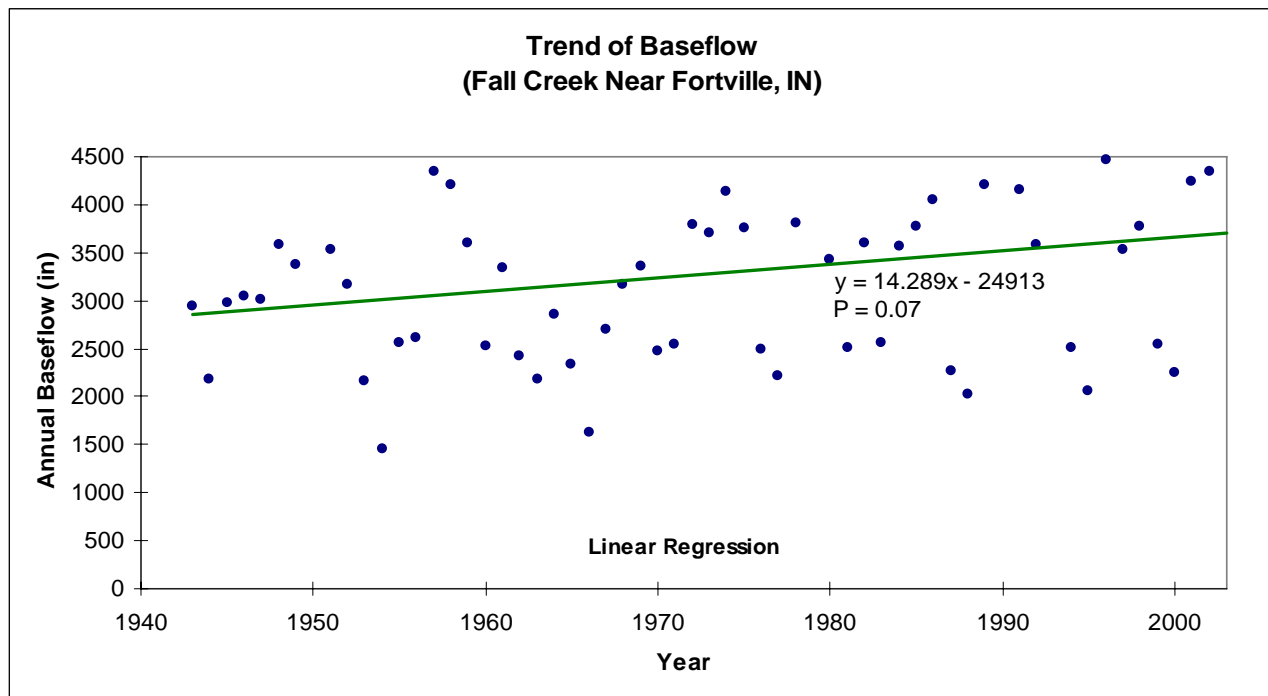


Figure 4. Increasing trend of baseflow in the watershed of Fall Creek near Fortville, IN.

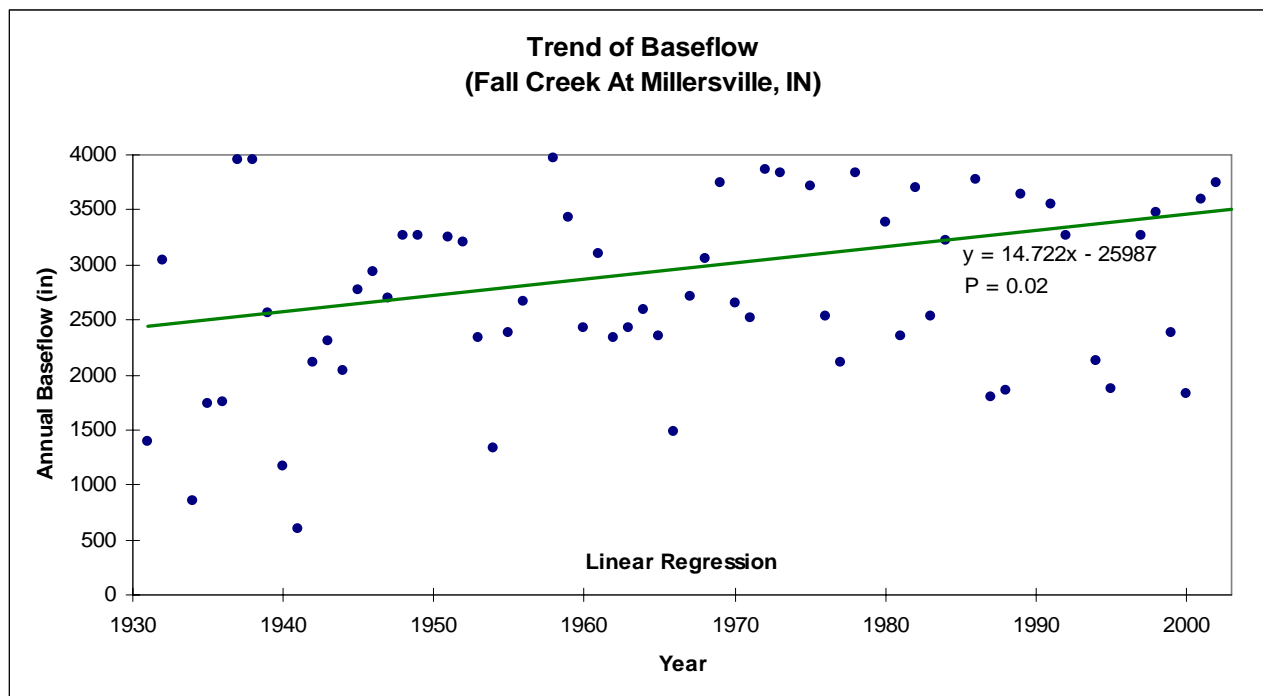


Figure 5. Increasing trend of baseflow in the watershed of Fall Creek near Millersville, IN.

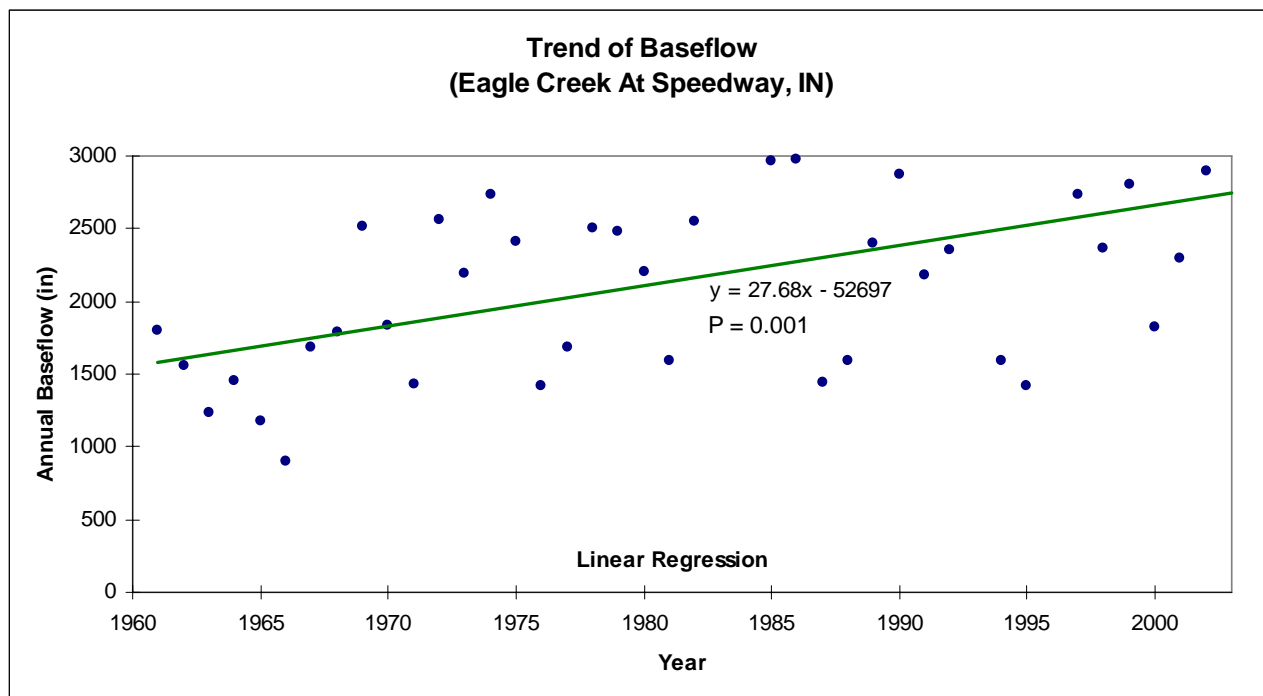


Figure 6. Increasing trend of baseflow in the watershed of Little Eagle Creek at Speedway, IN.

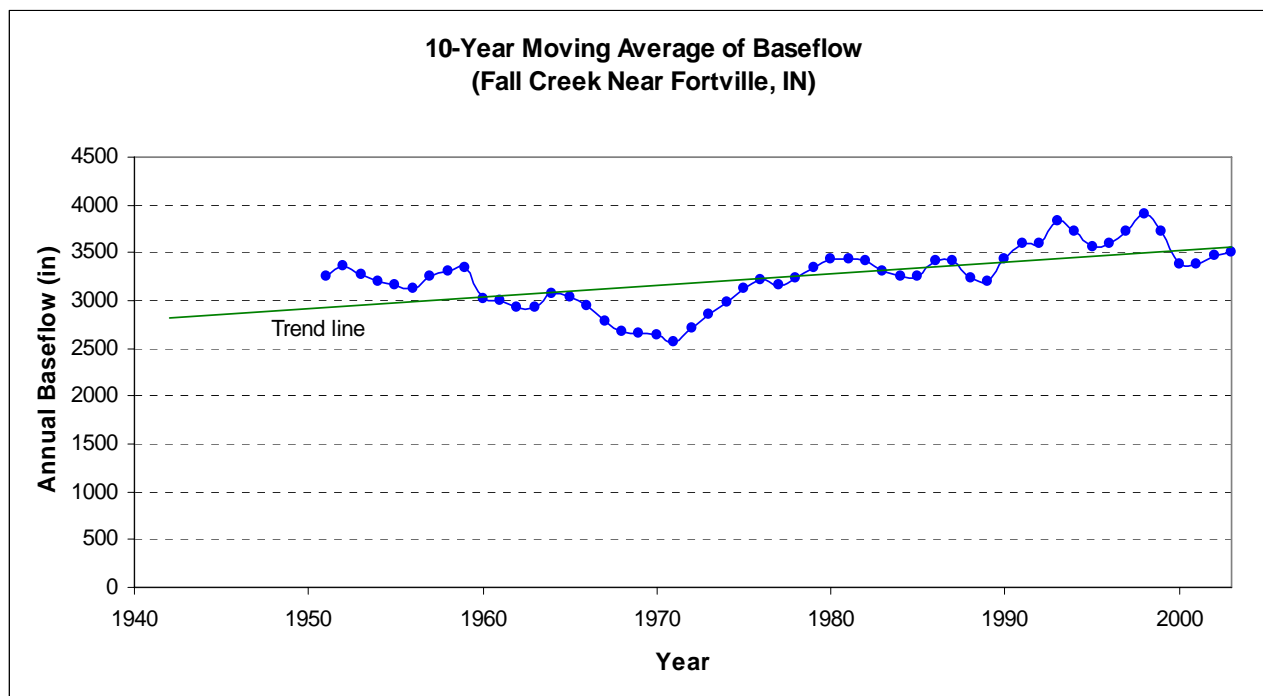


Figure 7. Increasing trend of baseflow in the watershed of Fall Creek near Fortville, IN.

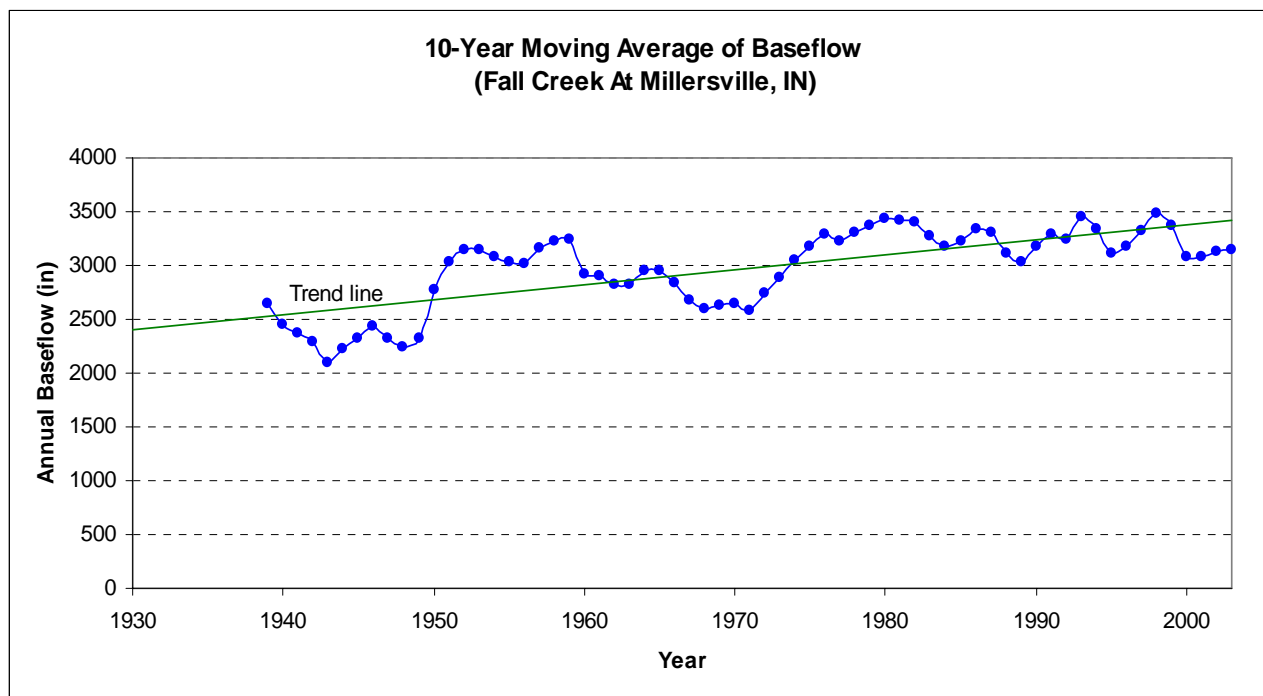


Figure 8. Increasing trend of baseflow in the watershed of Fall Creek near Millersville, IN.

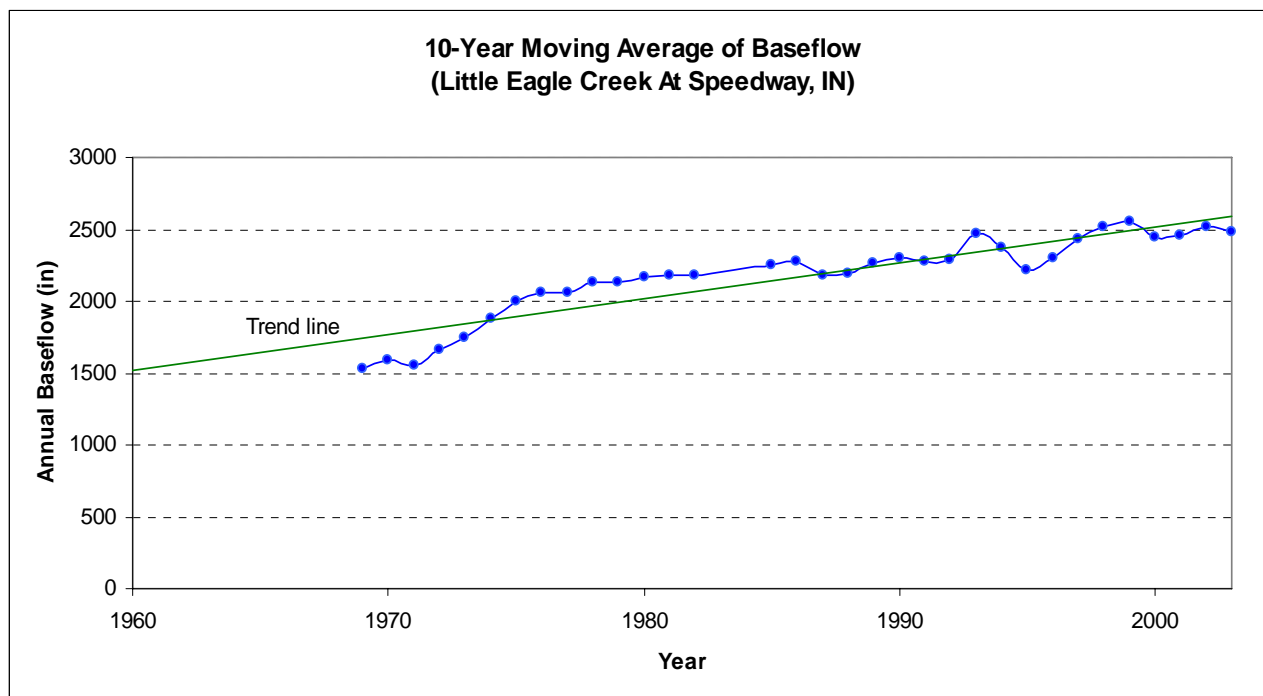


Figure 9. Increasing trend of baseflow in the watershed of Little Eagle creek at Speedway, IN.

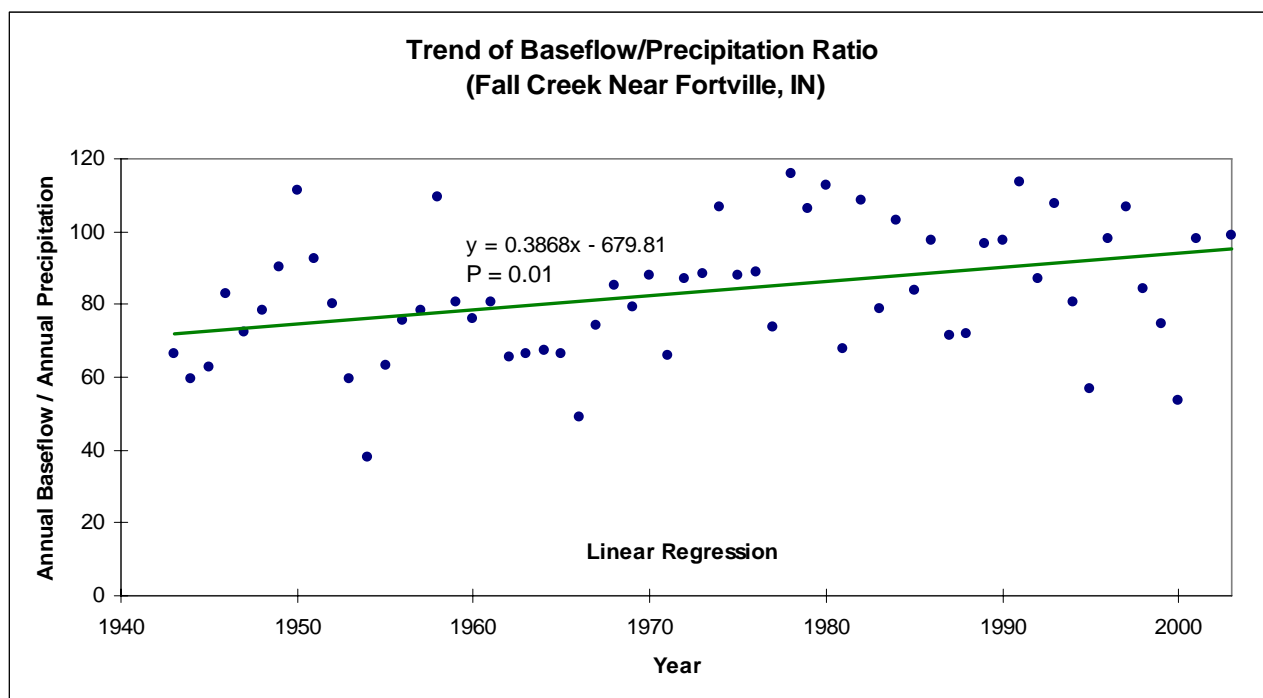


Figure 10. Increasing trend of baseflow in the watershed of Fall Creek near Fortville, IN.

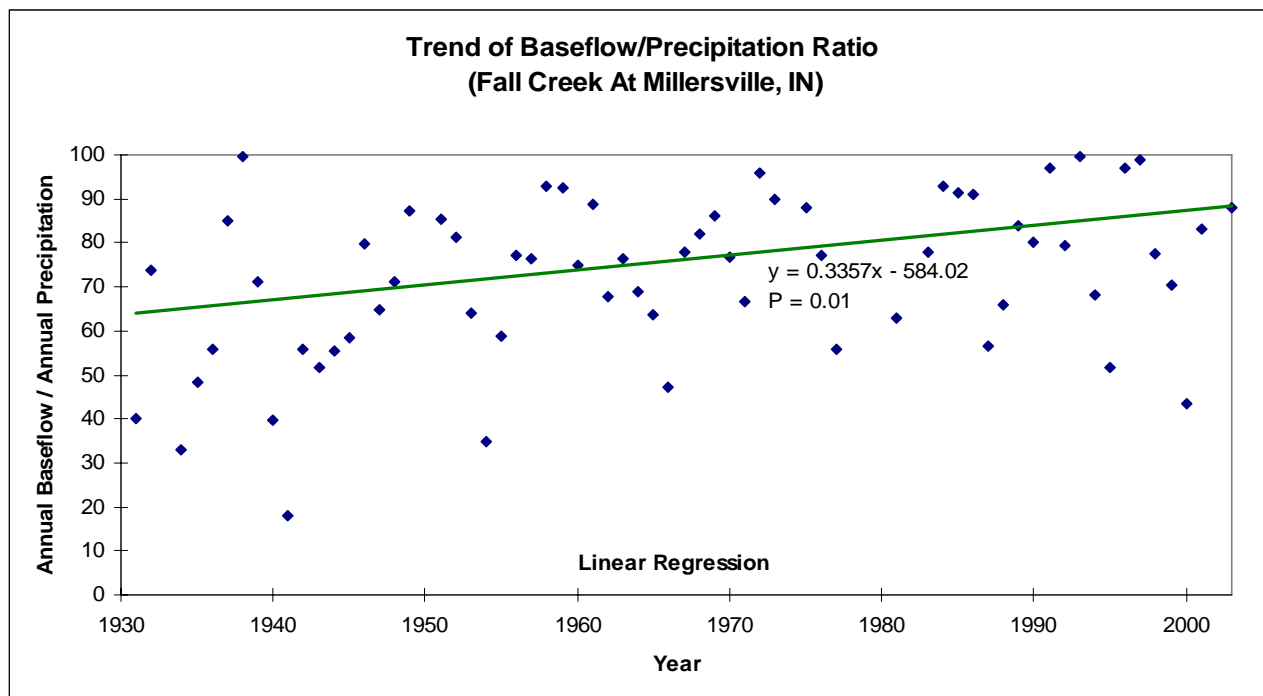


Figure 11. Increasing trend of baseflow in the watershed of Fall Creek near Millersville, IN.

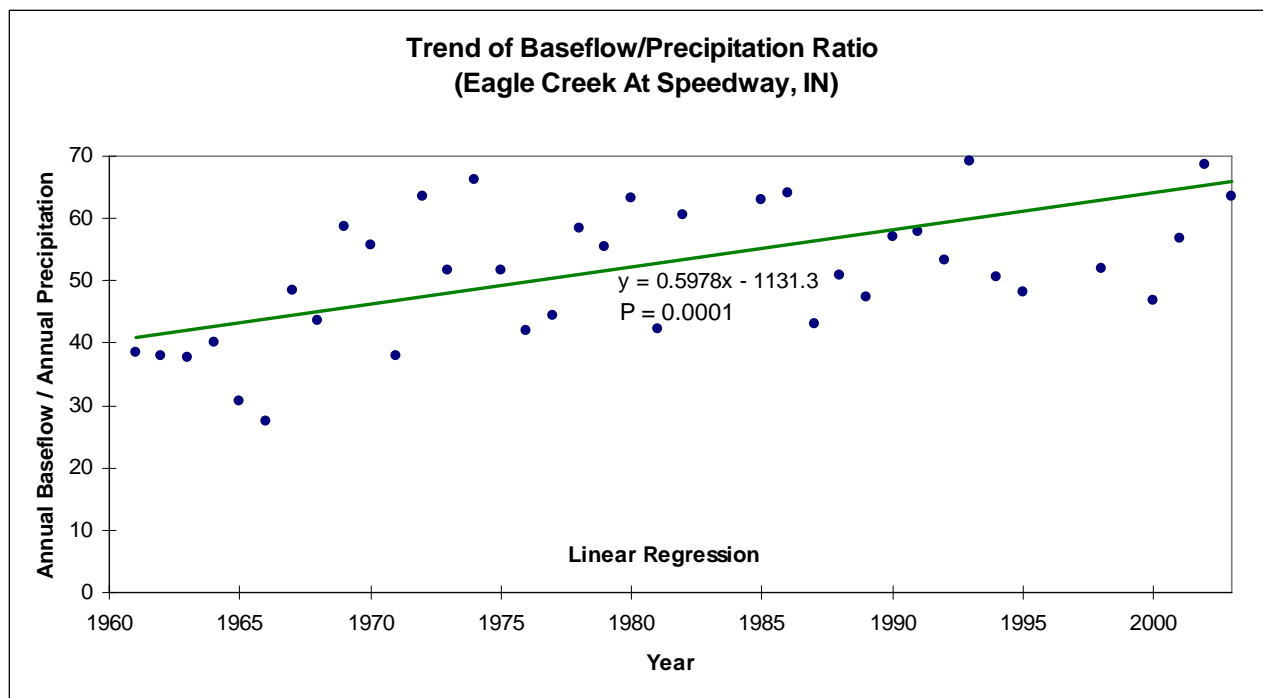


Figure 12. Increasing trend of baseflow in the watershed of Little Eagle creek at Speedway, IN.

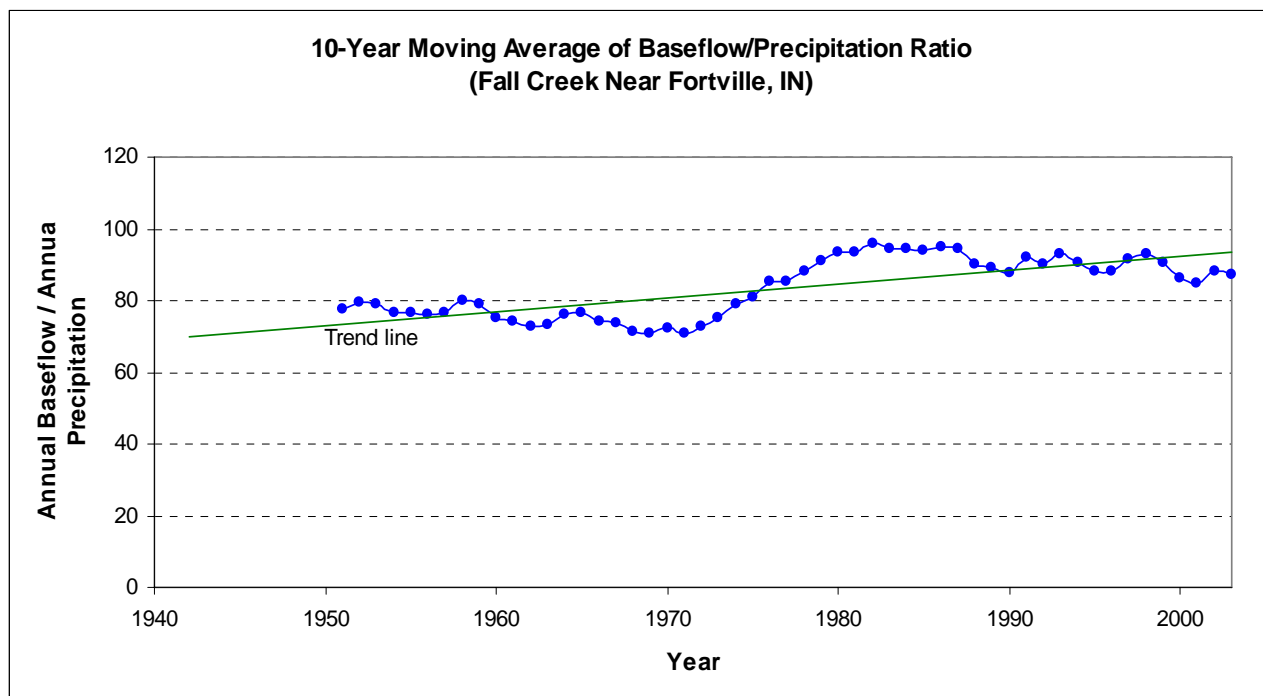


Figure 13. Increasing trend of baseflow in the watershed of Fall Creek near Fortville, IN.

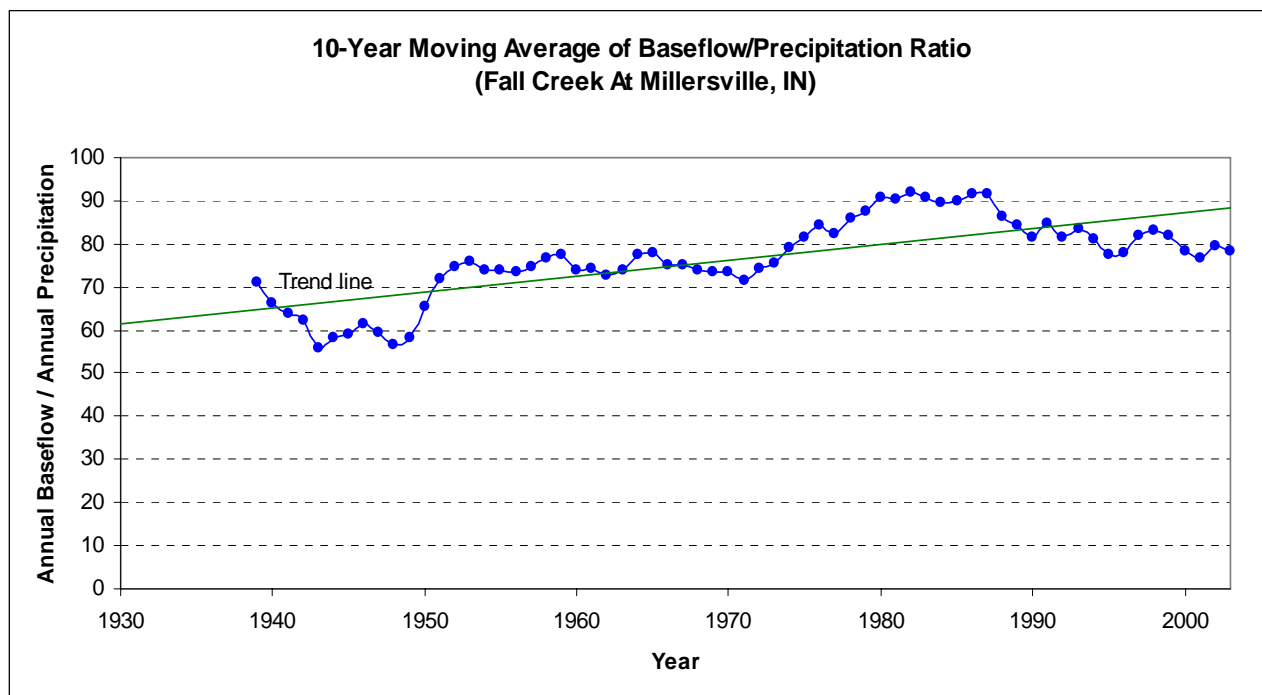


Figure 14. Increasing trend of baseflow in the watershed of Fall Creek near Millersville, IN.

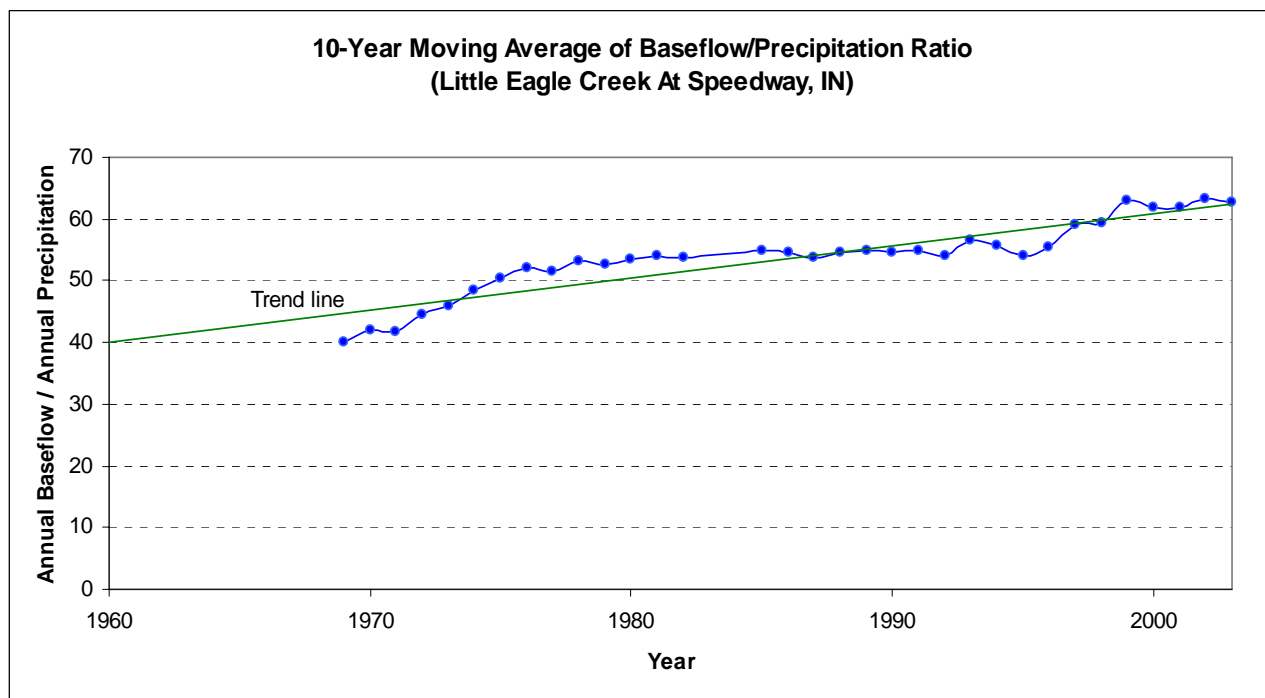


Figure 15. Increasing trend of baseflow in the watershed of Little Eagle creek at Speedway, IN.

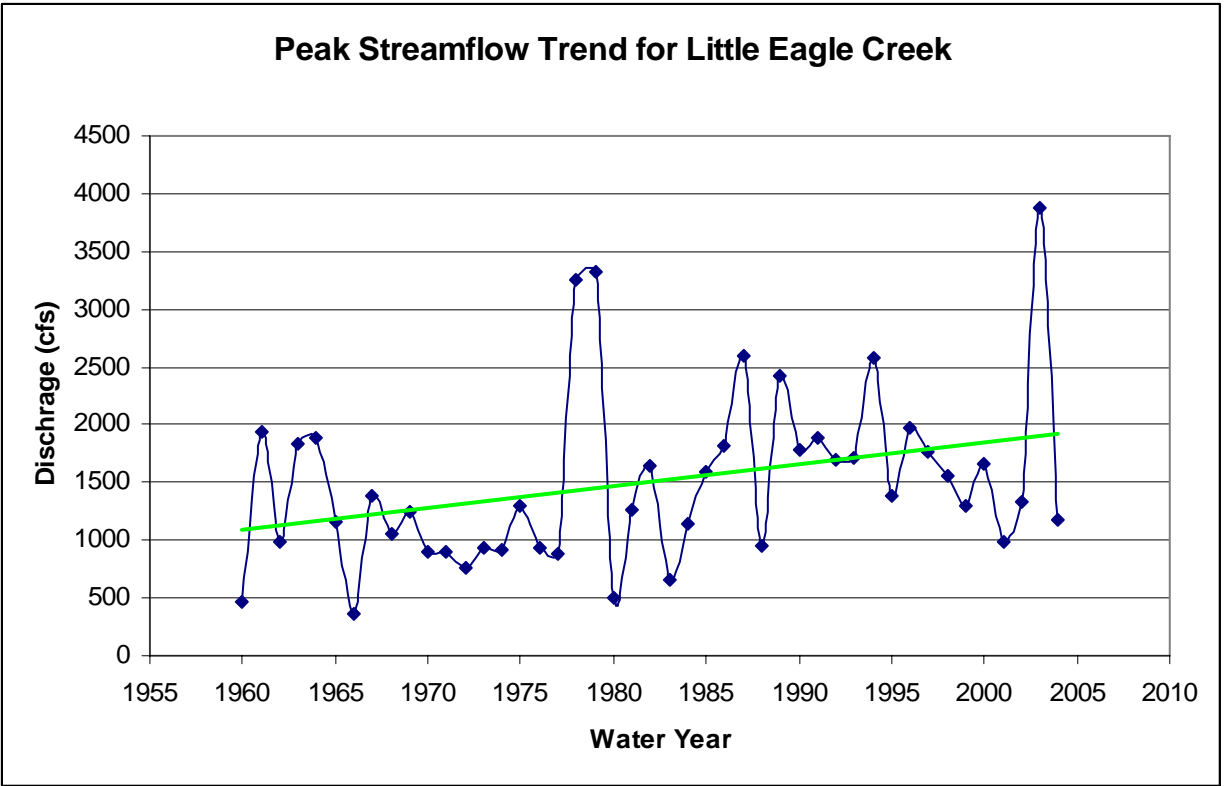


Figure 16. Statistically significant increasing trend in peak annual daily streamflow at Little Eagle Creek.

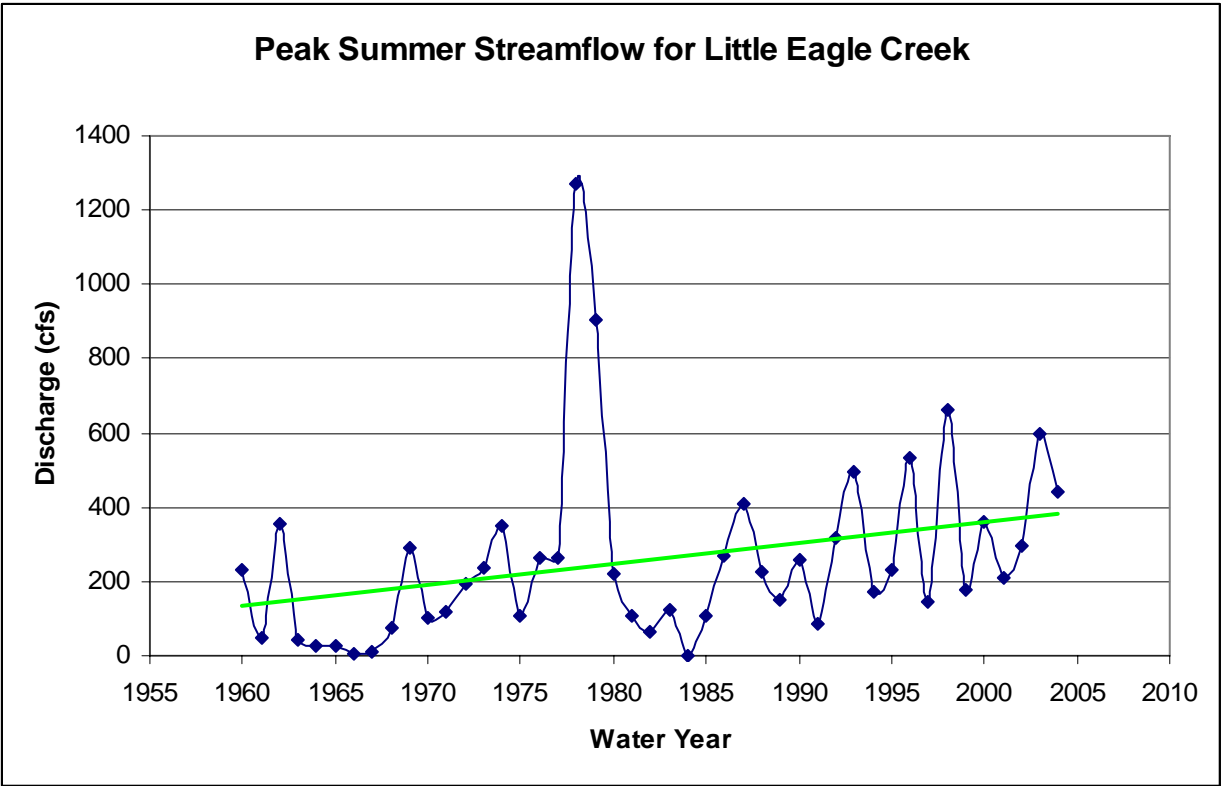


Figure 17. Statistically significant increasing trend in peak summer streamflow at Little Eagle Creek. Removal of the outlying points in 1978 and 1979 still results in a significant increasing trend.

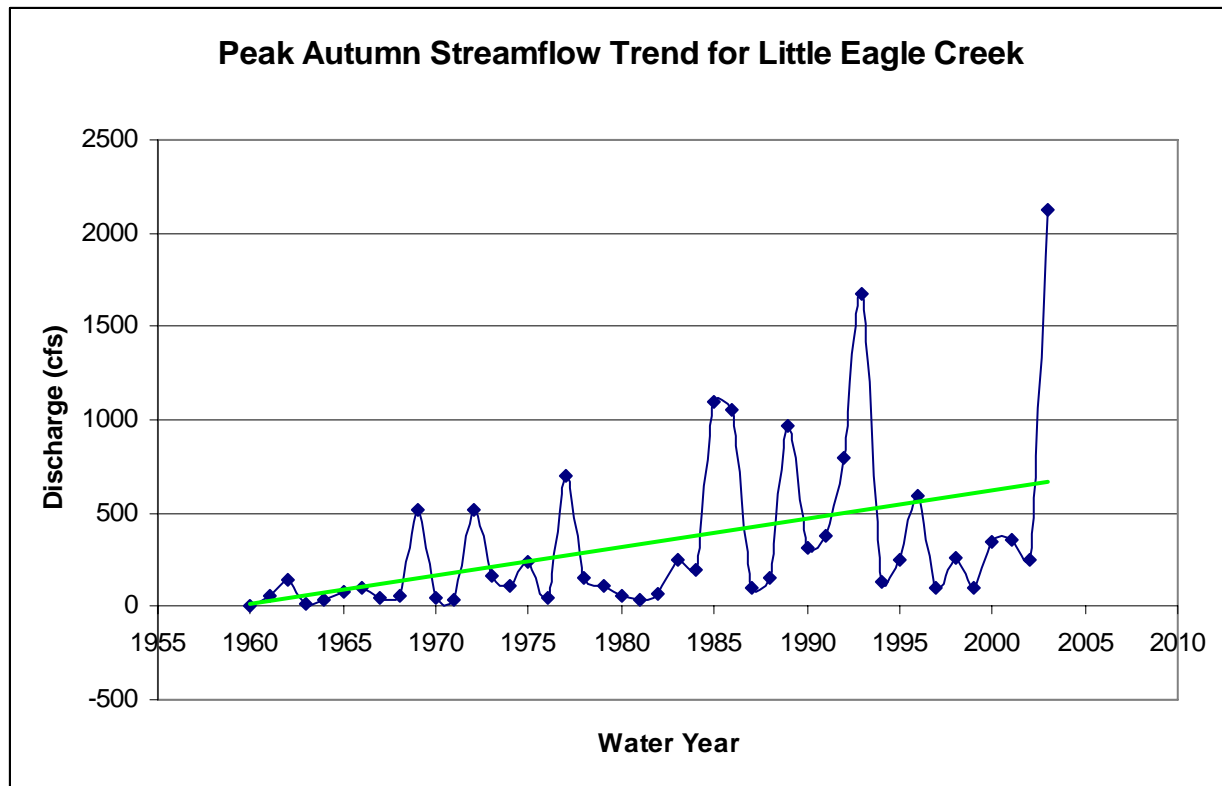


Figure 18. Statistically significant increasing trend in peak autumn streamflow at Little Eagle Creek.

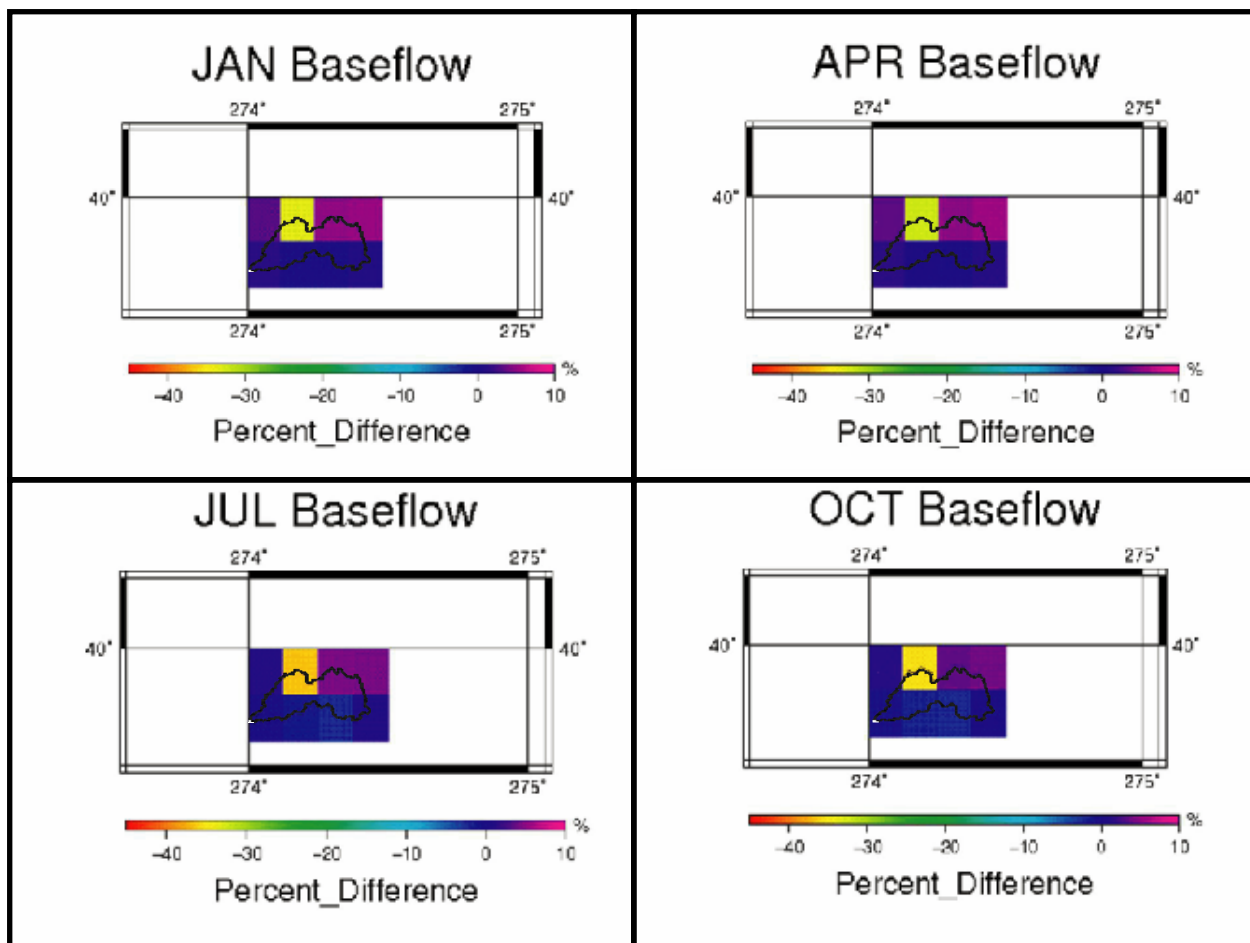


Figure 19. Percent difference between baseflow generated using 1940 and 2000 land use.

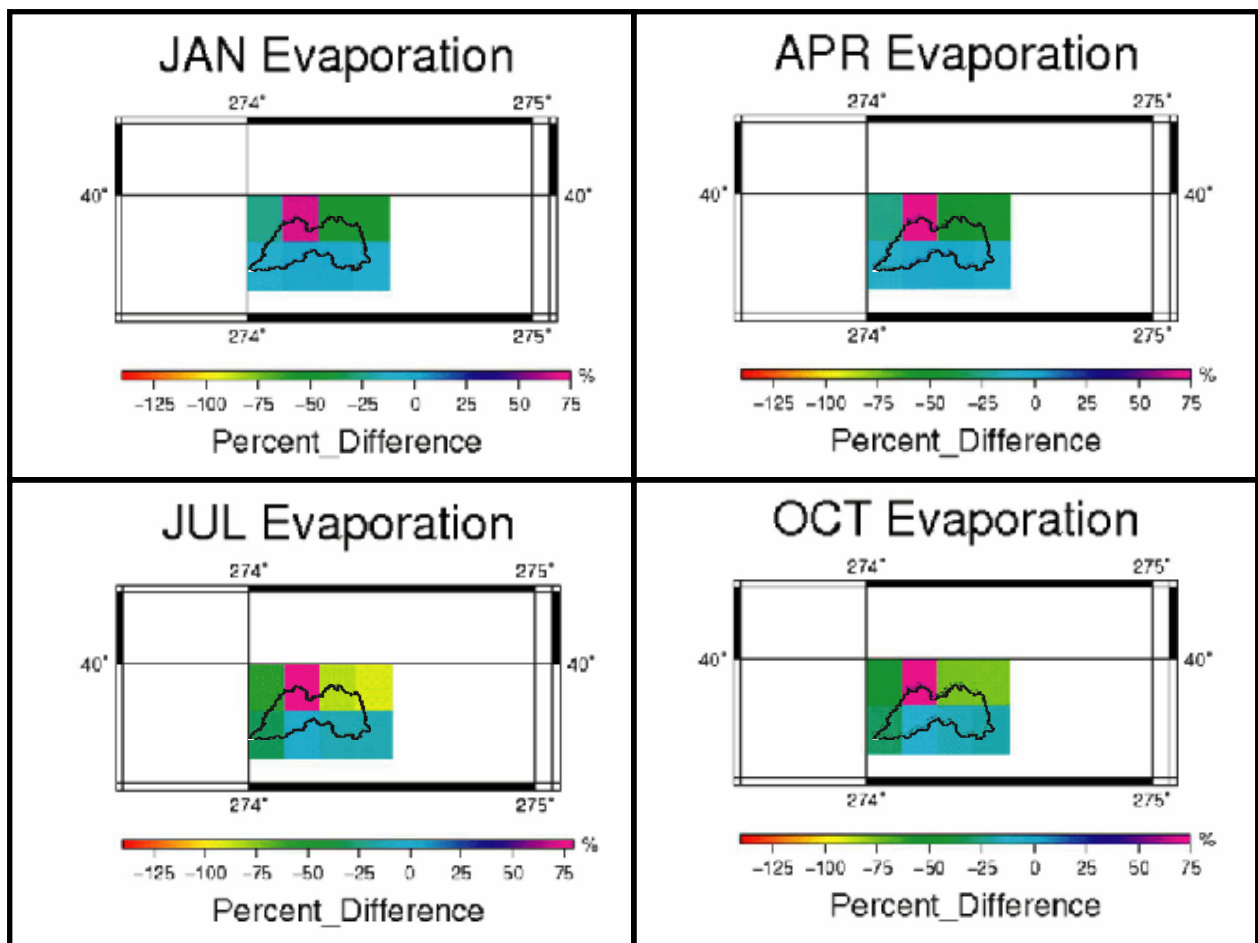


Figure 20. Percent difference between evaporation generated using 1940 and 2000 land use.

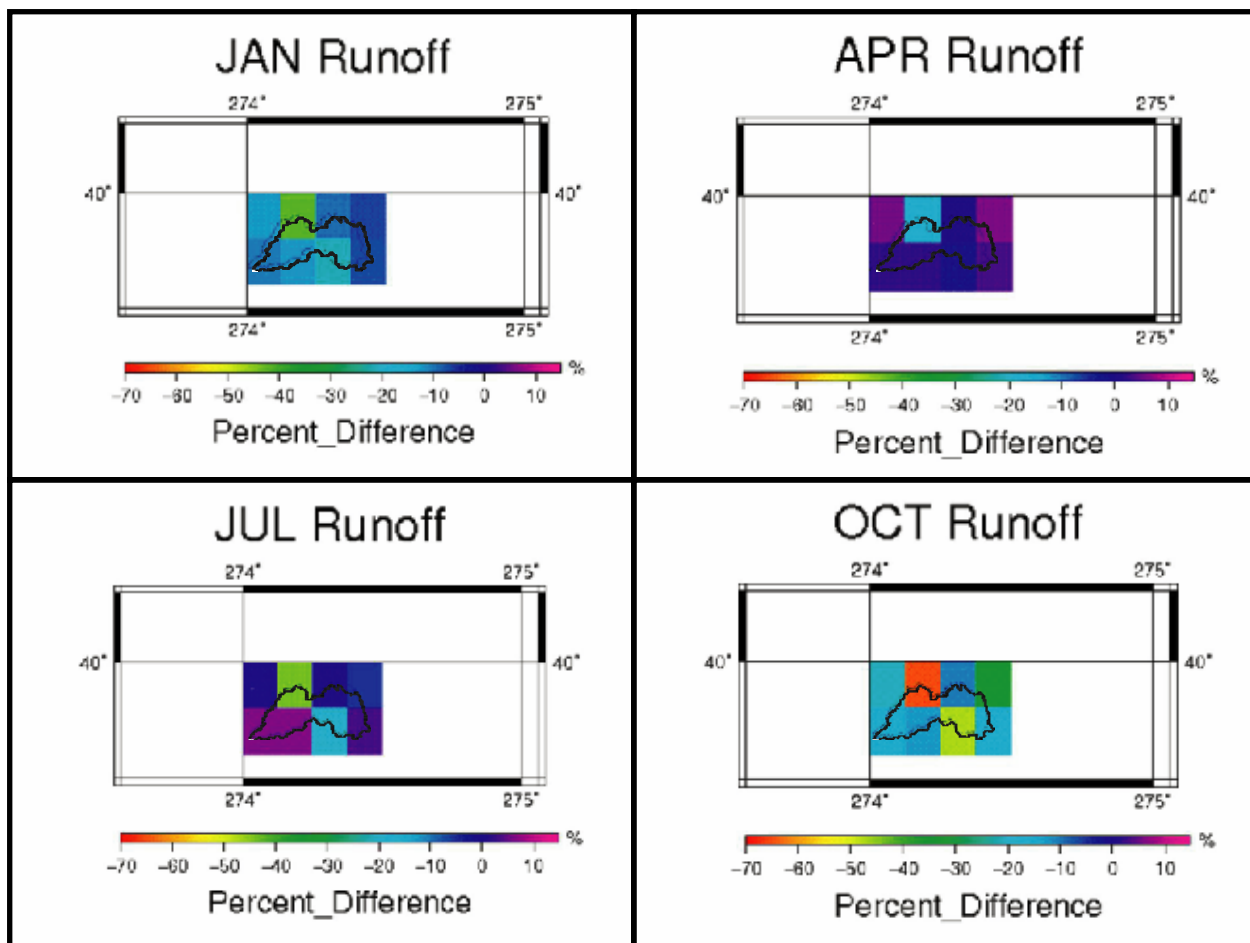


Figure 21. Percent difference between surface runoff generated using 1940 and 2000 land use.

Percent Difference in 1940 and 2000 Land Cover: Fortville Watershed

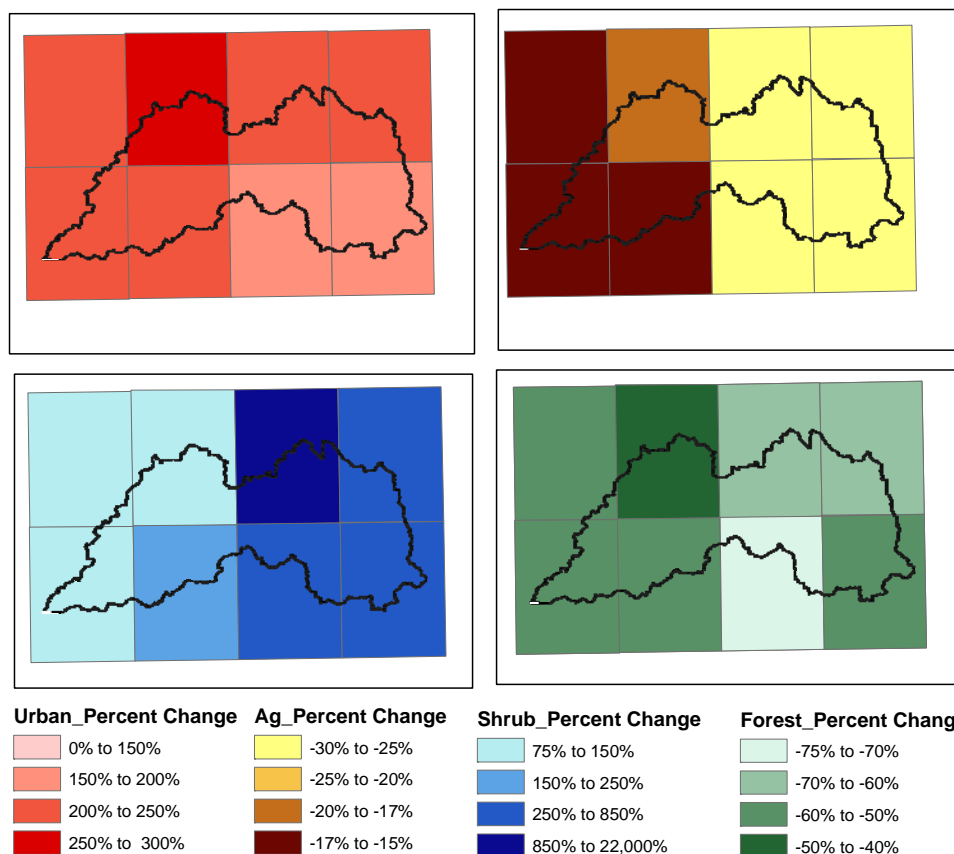


Figure 22. Estimated percent land cover change from 1940 to 2000 within the watershed draining to Falls Creek near Fortville, Indiana.

TABLE 1. Significance level of peak precipitation trends for the study sites. Values approaching zero are the most significant increases, while the values closer to one indicate decreases. Although not significant, peak annual precipitation is increasing, while peak autumn precipitation is increasing. The bold values indicate statistical significance at the $\alpha=0.05$ level.

	PEAK ANNUAL	PEAK WINTER	PEAK SPRING	PEAK SUMMER	PEAK AUTUMN
LITTLE EAGLE CREEK	0.641	0.737	0.081	0.50	0.045
FALL CREEK NEAR FORTVILLE	0.739	0.636	0.763	0.504	0.393
FALL CREEK NEAR MILLERSVILLE	0.727	0.373	0.601	0.717	0.251

TABLE 2. Significance level of total precipitation trends for the study sites. Values approaching zero are the most significant increases, while the values closer to one indicate decreases. The bold values indicate statistical significance at the $\alpha=0.05$ level.

	TOTAL ANNUAL	TOTAL WINTER	TOTAL SPRING	TOTAL SUMMER	TOTAL AUTUMN
LITTLE EAGLE CREEK	0.292	0.896	0.19	0.146	0.04
FALL CREEK NEAR FORTVILLE	0.739	0.636	0.736	0.504	0.393
FALL CREEK NEAR MILLERSVILLE	0.727	0.373	0.601	0.717	0.251

TABLE 3. Significance level of peak streamflow trends for the study sites. Values approaching zero are the most significant increases, while the values closer to one indicate decreases. The bold values indicate statistical significance at the $\alpha=0.05$ level. Peak annual streamflow is increasing at all sites, with peak summer and peak autumn streamflow showing the highest overall significance levels.

	PEAK ANNUAL	PEAK WINTER	PEAK SPRING	PEAK SUMMER	PEAK AUTUMN
LITTLE EAGLE CREEK	0.019	0.404	0.570	0.001	0.0001
FALL CREEK NEAR FORTVILLE	0.179	0.633	0.546	0.338	0.020
FALL CREEK NEAR MILLERSVILLE	0.182	0.273	0.187	0.026	0.004

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